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Poster paper

Thermo-mechanical analyses of beryllium compound refractive lens for NSLS-II beamline

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In this paper we discuss the finite-element analysis (FEA) of a one-dimensional beryllium compound refractive lens (Be-CRL) that was undertaken to study the feasibility of installing the CRL in the Inelastic X-ray Scattering (IXS) beamline of National Synchrotron Light Source-II (NSLS-II) (a new state-of-the-art medium-energy third-generation storage ring). The current insertion device for this beamline is an IVU22-6m in-vacuum planar undulator delivering a total power of ~9 kW with a peak power density of ~90 kW/mrad^2. Through analysis, based on calculation of spectral angular distribution of undulator radiation from IVU22, we determined that it is essential to install a 30 μm graphite filter upstream of the CRL in order to restrict the temperature rise in the CRL to 65°C for acceptable thermal strain.

1. Introduction

Finite-element analysis (FEA) analyses were performed on a beryllium compound refractive lens (Be-CRL) for the IXS beamline of NSLS-II. The insertion device for this beamline is IVU22-6m which is located in the high-β straight section and delivers a total power of ~9 kW with an on-axis power density of 90 kW/mrad^2. In the current design concept, three holes (1 mm diameter) with a parabolic profile will be machined using electro-discharge machining in a Be block yielding three CRLs in series (figure 1). The parabola is defined by a minimum wall thickness of 100 μm at the vertex of the parabola and a curvature of 0.247 mm at the apex of the lenses. The CRL block will be brazed to a copper holder, which in turn will be bolted to a water-cooled copper mask with an aperture of 1 mm. At a distance of 20 m from the source, the CRL will see an incident power of 225 W within the 1 mm aperture.

2. Heat load analyses – Be-CRL

For the FEA only one-half of the CRL and the copper holder assembly was modelled using ANSYS Workbench software to take advantage of the symmetry. Across the minimum thickness (100 μm) at the vertex of the parabola, a mesh resolution of

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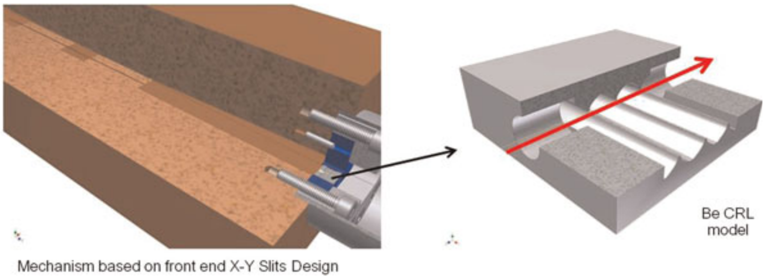

FIGURE 1. Be-CRL assembly. The equation of the parabolic CRL profile is given by $y = \pm y_0 \pm (1/2R)x^2$, with $y_0 = 0.05$ mm and $R = 0.24693$ mm the curvature of the vertex.

10 μm was deemed to be adequate for accurate calculation of the volume power deposition in beryllium as a function of depth using Synchrotron Radiation Workshop (SRW) code. The upstream face of the copper holder which is in contact with the water-cooled copper mask was assumed to be at 25°C. A non-linear FEA using temperature-dependent material properties of beryllium (Dombrowski *et al.* 1995); (Watson *et al.* 1997) showed that a peak-absorbed power/unit volume in the first CRL of 1000 W/mm^3 resulted in a maximum temperature of ~210°C (figure 2*a*) and a plastic strain of ~2% (figure 2*b*).

A relationship between total strain (%) vs. fatigue life (cycles) was developed for beryllium (figure 3) by substituting the experimental low cycle fatigue life parameters available in the literature (Ganesh *et al.* 2002) in the Coffin–Manson fatigue life correlation (Manson & Hirschberg 1964). A fatigue life of <100 cycles corresponding to 2% strain implies that the CRL will not be able to handle the direct undulator radiation power.

Further calculations using SRW code showed that using a 30 μm thick graphite filter in front of the Be-CRL considerably reduces soft X-ray content in the spectrum of the undulator radiation entering the CRL (figure 4).

This will reduce the peak volume power density absorbed in the CRL by a factor of 10 and the absorbed power by a factor of 2.4 (figure 5*a*). This reduction in the heat load comes with minimum penalty for the flux at ~9 keV photon energy, which will be mostly used by the beamline (total reduction in the useful photon flux due to the combined effect of the graphite filter and the Be-CRL <10%).

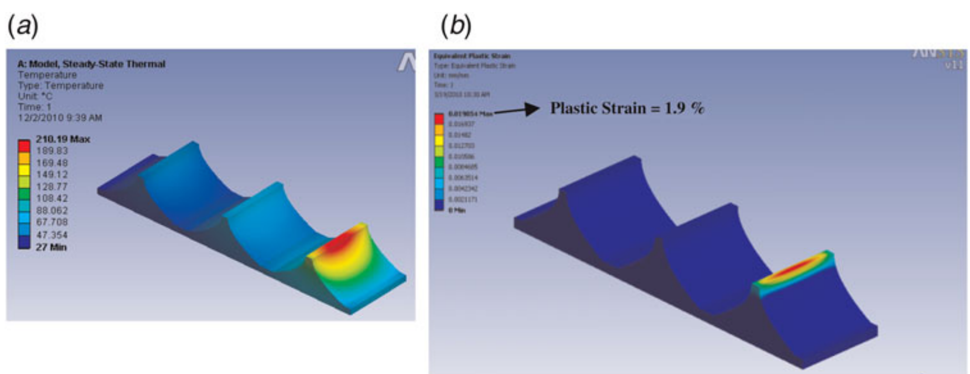

FIGURE 2. (*a*) Temperature plot of first CRL, $T_{max} = 210$°C; (*b*) equivalent plastic strain plot of first CRL, $\varepsilon_{pmax} = 1.9$%.

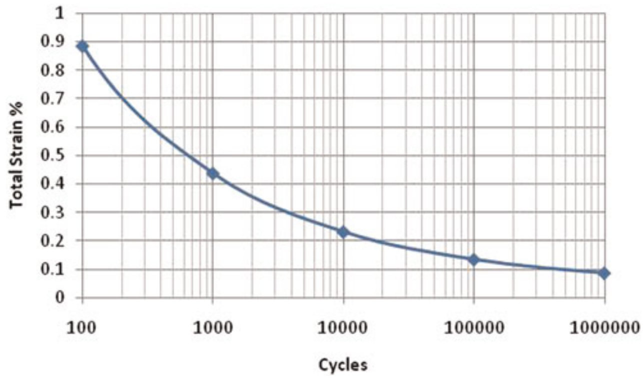

FIGURE 3. Strain vs. fatigue life for beryllium.

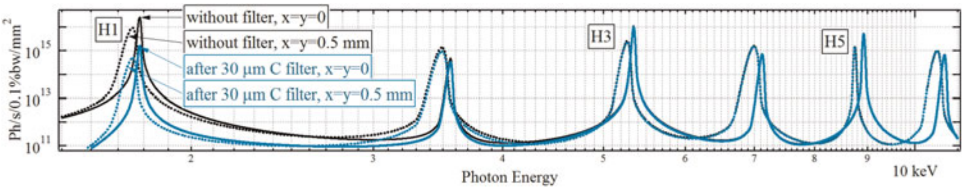

FIGURE 4. Undulator radiation spectral flux per unit surface at two different positions in a transverse plane before CRL, without filter and after 30 μm thick graphite filter.

The resulting peak temperature in the CRL is ~65°C (figure 5*b*), which results in a total strain of ~0.1% (mostly elastic) and negligible plastic strain (figure 6*a*,*b*). The corresponding fatigue life will be >1 million cycles, which can be considered to be a safe design option.

The FEA findings are consistent with the fact that beryllium is brittle (4% elongation at failure) and can hardly withstand any plastic deformation. Because of the small thermal strain at 65°C, as expected, SRW calculations showed that optical properties of the CRL are not affected by the heat load. FEA performed for the

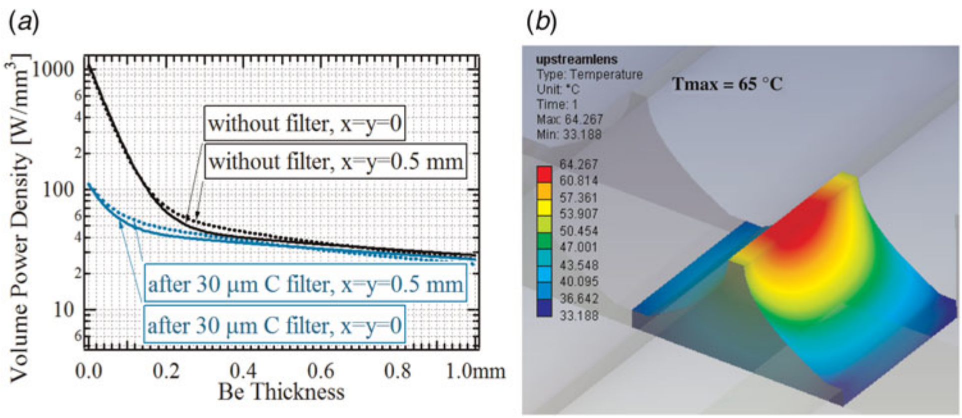

FIGURE 5. (*a*) Absorbed power/unit volume with and without graphite filter; (*b*) temperature of first CRL – $T_{max} = 65°C$.

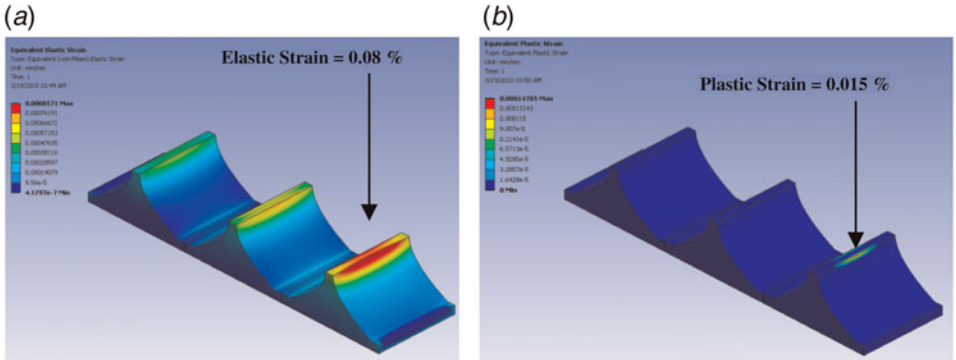

FIGURE 6. (*a*) Elastic strain plot, $\varepsilon_{emax} = 0.08$ %; (*b*) plastic strain plot, $\varepsilon_{pmax} = 0.015$ %.

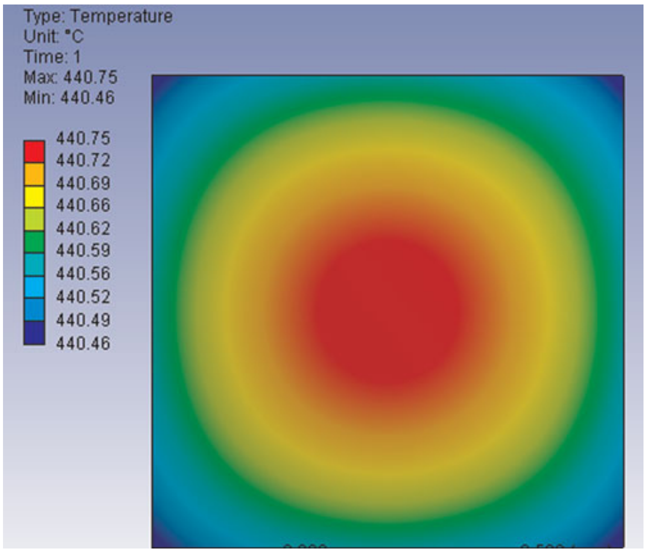

FIGURE 7. Temperature plot of graphite filter, $T_{max} = 440$°C.

upstream graphite filter (30 μm thick, 50 mm long, 50 mm wide) assuming that the heat is lost to the ambient by radiation showed that an absorbed power of 55 W in the filter results in a peak temperature of 440°C (figure 7). There is a safety margin of ∼1200°C between the maximum filter temperature and the onset of significant vaporization

3. Conclusions

A feasibility study of placing a Be-CRL in the IXS beamline of NSLS-II at a distance of ~20 m from the source (IVU22-6m) was carried out. Non-linear thermal and structural FEA of the Be-CRL indicated that pre-filtering with a 30 μm graphite filter with minimum flux penalty (<0 % total) was necessary, to reduce the undulator heat load and to restrict the resulting temperature and strain in the CRL to acceptable values of 65°C and <0.1 %, respectively.

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